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SIMULATION OF A NANOFLUID-BASED ANNULAR SOLAR COLLECTOR

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Abstract

A numerical study of convective heat transfer in an annular pipe solar collector system (**Fig. 1**) is conducted. The inner tube contains pure water and the annular region contains nanofluid. Three-dimensional steady-state incompressible laminar flow comprising water-based nanofluid containing a variety of metallic nano-particles (copper oxide, aluminium oxide and titanium oxide nano-particles) is examined. The Tiwari-Das model is deployed for which thermal conductivity, specific heat capacity and viscosity of the nanofluid suspensions is evaluated as a function of solid nano-particle volume fraction. Radiative heat transfer is also incorporated using the ANSYS solar flux and Rosseland radiative models. The ANSYS FLUENT finite volume code (version 18.1) is employed to simulate the thermo-fluid characteristics. Mesh-independence tests are conducted. The influence of volume fraction on temperature, velocity, pressure contours is computed and visualized. Copper oxide nanofluid is observed to achieve the best temperature enhancement. Temperature contours at cross-sections of the annulus are also computed.

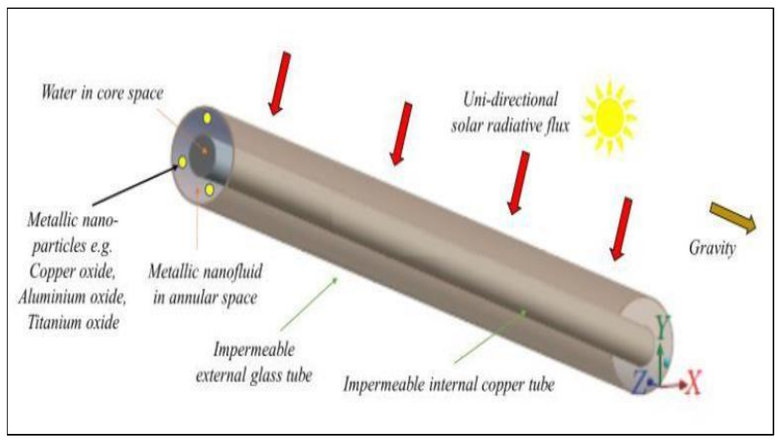


Fig. 1: Geometrical and physical model for annular nanofluid solar collector

MATHEMATICAL MODEL

The three-dimensional models of heat and fluid flow in the solar collector tube are designed in ANSYS FLUENT computational fluid dynamics software. Laminar, steady-state, incompressible flow is considered with forced convective heat transfer. The annular nanofluid is the absorber fluid and the Tiwari-Das nano-particle volume fraction model is deployed **[1].** The fundamental equations for steady viscous, incompressible laminar flow are the three-dimensional time-independent Navier-Stokes equations, which in a Cartesian coordinate system, take the following form:

D'Alembert mass conservation (3-D continuity)

$$\left[\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right]=0$$

x-direction momentum conservation

$$\rho\left[u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right]=\rho F_x-\frac{\partial p}{\partial x}+\mu\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right]$$

The same in y and z direction

The appropriate energy conservation equation is:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\alpha_m\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+Q_{rad}$$

Tiwari-Das model allows different concentrations (volume fraction) and types of metallic nano-particles. Where nano fluids properties can be calculate from follow equation:

$$\phi=\frac{v_{np}}{vf},\ \mu nf=\frac{\mu f}{(1-\phi)^{2.5}},\ \rho nf=(1-\phi)\rho f+\phi\rho s,$$

$$Cpnf=\frac{(1-\phi)(\rho Cp)f+\phi(\rho Cp)}{s\rho nf},\ \frac{Knf}{kf}=\frac{ks+2kf-2\phi(kf-ks)}{ks+2kf-\phi(kf-ks)}$$

Here φ=volume fraction, Vnp=nano particles volume and Vf =volume of fluid, μ_{nf}= dynamic viscosity of nanofluid (kg/m.s), μ_f= dynamic viscosity of base fluid. ρnf=nanofluid density, ρf=base fluid density, ρs=nanoparticle density, $Cpnf$=nanofluid specific heat, knf =nanofluid thermal conductivity, kf= fluid thermal conductivity and ks = nanoparticle thermal conductivity.

ANSYS FLUENT Boundary condition and radiation model

At the inlet: Volume flow rate inlet of 0.002 kg/s

At the outlet: Zero pressure outlet from one face.

Heat flux: Heat is added as the sun radiation intensity of 877 w/m^2. In ANSYS FLUENT physics, gravity is set as 9.81 m/s^2.

Radiative heat transfer is also incorporated using the ANSYS **solar load model** and **Rosseland radiative models**. The ANSYS FLUENT finite volume code **[2]** is employed to simulate the thermo-fluid characteristics.

ANSYS FLUENT CFD Method

Fig. 2 shows the ANSYS methodology employed for the CFD simulations (SIMPLE). **Fig. 3a** shows the ANSYS FLUENT full hex element mesh and **Fig. 3b** shows the mesh cross-section used.

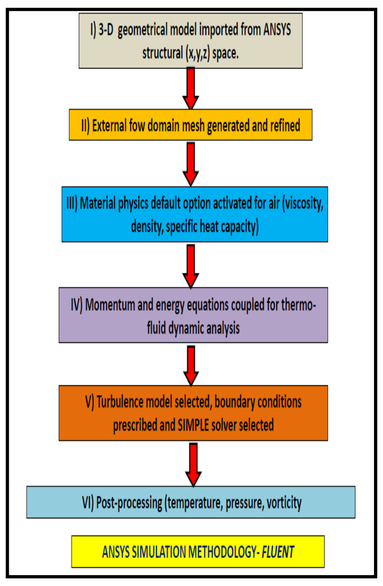
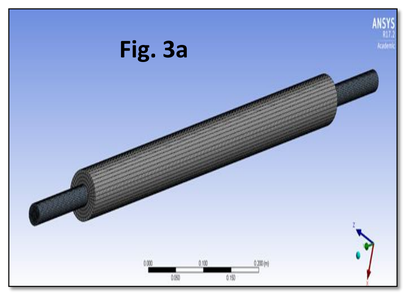
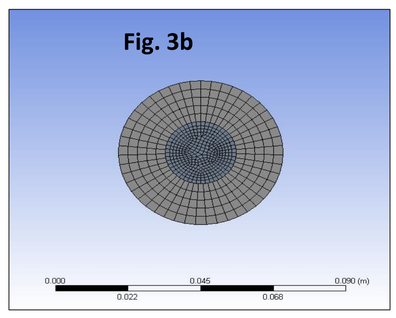


Fig. 2





Grid Study

Fig. 4 shows the grid sensitivity analysis. The largest elements used in case one can be considered as a coarse mesh with 103068 elements. On increasing the number of elements by 100000 (case two), the graph shows a variation indicating that the simulation is not convergent. The next part of the grid dependent study covers cases three, four and five. Upon observation of cases four (325951 elements) and five (448836 elements), these cases utilize a fine mesh, where the difference between the two values are infinitesimal and hence considered negligible. This shows that the simulation is convergent at case four with 448836 elements. This grid-independence study provides an appropriate grid size (case four) which is subsequently adopted for all further simulations and is of sufficient quality to guarantee mesh-independent and converged results i.e. the most accurate results possible with the minimum number of elements.

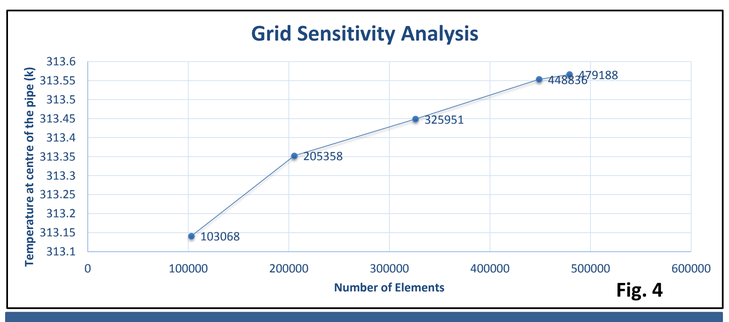
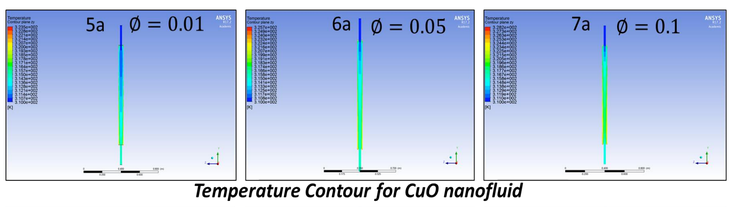


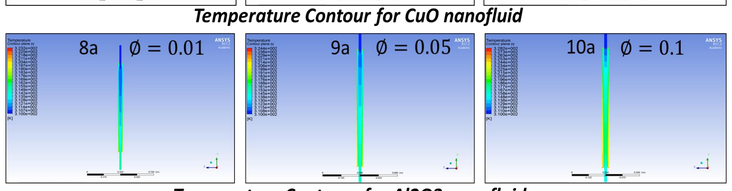
Fig. 4

Results &Discussion

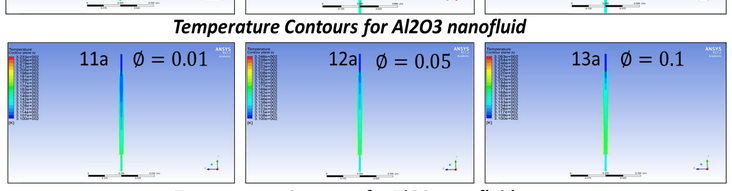
5a, 6a and 7a show a significant modification in temperature distributions as volume fraction is enhanced from Ø= 0.01, to Ø= 0.05 and finally Ø=0.1. There is progressive heating from the base upwards of the annular region with increasing volume fraction. The blue zones are progressively eliminated, and green zones (higher temperature) extend further towards the upper adiabatic end. Red (maximum temperature zones) begin to appear at the highest volume fraction (**fig. 7a**). The increase in concentration of metallic nano-particles clearly enhances thermal conductivity of the nanofluid in the annular region and this intensifies thermal diffusion and heat transfer (**figs. 11a, 12a, 13a**) The temperature magnitudes exceed those computed at the same values of volume fraction for Aluminium oxide (**figs. 8a, 9a, 10a**) but are substantially lower than those obtained for Copper oxide (**figs. 6a, 7a, 8a**). This confirms the superior performance of Copper oxide in achieving thermal enhancement in the solar annular collector.



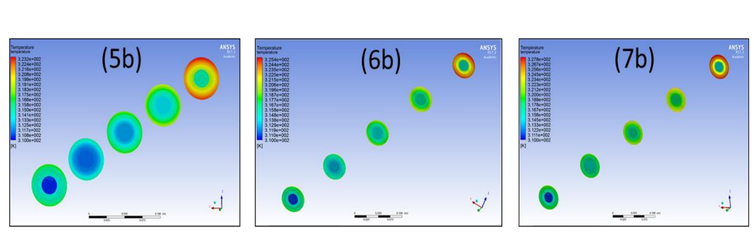
Temperature Contour for CuO nanofluid



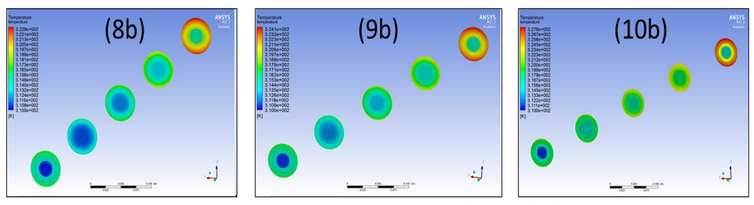
Temperature Contours for Al2O3 nanofluid



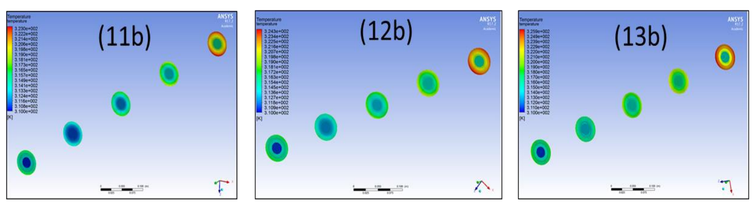
Temperature Contours for TiO2 nanofluid



Temperature Contour cross sections for CuO nanofluid



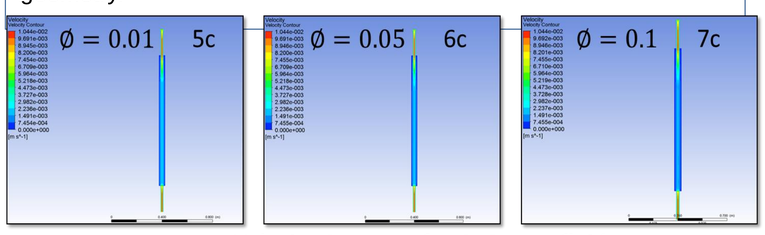
Temperature Contour cross sections for Al_2O_3 nanofluid



Temperature Contour cross sections for TiO_2 nanofluid

Fig. 11b, 12b and 13b (temperature cross-section slice views) also show that temperatures are markedly enhanced with increasing volume fraction of titanium oxide nano-particles, as we progress from the lower end of the annular region to the upper end. Stronger red (high temperature) and yellow zones (quite high temperature) appear to grow considerably. The magnitudes achieved are larger than those for the Aluminium oxide cases (**figs. 8b, 9b and 10b**). However, they are still somewhat less than those attained for the Copper oxide cases (**figs. 5b, 6b and 7b**). Apparently therefore higher nano-particle concentrations (volume fractions) of Copper oxide attain the best thermal performance since the best absorption of solar thermal energy is achieved. Intensified thermal convection currents are generated for this case. Titanium oxide is the next best option, whereas Aluminium oxide is the least successful option. These findings are important since they generalize previous studies in which a single metallic nano-particle was examined e.g. Copper oxide by Moghadam et al. **[3]** or two metallic nanofluids (silver oxide and aluminium oxide) by Maddah et al. **[4].**

Figs. 5c, 6c and 7c illustrate the evolution in velocity through the annular space. A less tangible influence is computed with increasing volume fraction. In all case high velocity zones arise at the inlet and outlet with slower zones in the interim sections. The primary influence on velocity is via the viscosity modification in the Tiwari-Das model. Although there is a slight intensification in velocity i.e. flow acceleration at the highest volume fraction (**fig. 7c**), this is only identified in the extremity zones of the annular geometry.



Velocity Contours for CuO nanofluid

Conclusions

(i) Copper oxide nanofluid is observed to achieve the best temperature enhancement. Temperature contours at cross-sections of the annulus are also computed.
(ii) Titanium Oxide achieves higher temperatures than Aluminium Oxide but significantly lower temperatures than Copper Oxide.
(iii) Temperature cross-sections exhibit significant enhancement in magnitudes with volume fraction for all three metallic nano-particles, although the best performance again is with Copper Oxide.
(iv) There is flow acceleration for the Copper oxide case at the highest volume fraction although it is confined to the extremity zones of the annular geometry (inlet and outlet).
(v) Velocities are initially increased with volume fraction for the Aluminium Oxide case but subsequently with maximum volume fraction they are reduced.
(vi) Pressures are also reduced somewhat with increasing volume fraction for the Copper oxide case and not altered significantly for either Titanium Oxide or Aluminium Oxide cases.

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